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INTENSITY CORRECTION AND DYNAMIC RANGE EXPANSION FOR DIGITAL X-RAY RADIOGRAPH IMAGES

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INTRODUCTION

Quantitative and qualitative analysis of NDE radiograph film is often accomplished using image processing tools. A prerequisite for such analysis is transformation of the data contained in the physical x-ray film into discrete numerical data suitable for image processing. Such transformation, called image acquisition or digitization, will introduce noise and spurious information (artifacts) into the original data. While certain qualitative data enhancement processes are tolerant of these data anomalies, significant errors may preclude quantitative analysis such as flaw sizing or flaw detection.

In this paper, a method is presented to model some of the imperfections in the image acquisition step in an attempt to compensate their effects. In particular, techniques for compensation of intensity nonlinearities and dynamic range limitations will be described.

SYSTEM-INTRODUCED ERRORS

In a typical low-cost image acquisition system, the x-ray film is placed on a fluorescent bulb-based lightbox above which a CCD or tube-based camera is carefully positioned. Scanning circuitry in the camera continuously images the film and produces a video signal corresponding to the full video frame. A frame grabber then captures exactly one frame of the video signal and samples it at a finite resolution (usually 480 lines of 512 pixels), quantizing the signal at each point into typically 256 intensity levels. The digitized version of the film thus obtained is then stored as an array in memory for subsequent processing.

Many errors are introduced by such an acquisition system. Flicker inherent in the lightbox tube occurs at frequencies that are not high relative to the camera scan rate. Furthermore, the rectangular surface of the lightbox is illuminated by a non-rectangular tube. These two factors together contribute to producing a lightbox surface illumination that is both spatially dependent and time varying.

The camera lens has internal reflections and surface aberrations that produce geometric and intensity errors. The camera image sensor sensitivity often varies over the sensor surface. Scanning of the sensor produces distortions at the start and end of each scanned line.

The frame grabber employs an analog-to-digital conversion process which introduces quantization errors in the data. Clipping of the input signal in this process and sensitivity restrictions also contribute to saturation.

INTENSITY CORRECTION

Obtaining numerically correct image data requires compensation of two types of system nonlinearities: intensity and geometric.

Ideal system intensity response requires a coherent, time invariant illumination source, linearity of camera response to incident illumination, and linear analog-to-digital conversion. Actual system intensity response is generally not constant over the image frame and degrades as the object off-camera-axis distance is increased. Ideal response correction must therefore account for the actual location of data within the image frame.

Correction schemes involve modeling response nonlinearities over the entire image frame and using the model to compensate the actual response. Selection of a proper response model is vital to accurate compensation. Ideally, the response of every pixel in the image frame should be modeled using coherent point-source illumination such as laser light. Alternatively, each location in the image frame could be illuminated by every possible incident light intensity from a dispersive illumination source such as a lightbox. Neither of these is practical due to illumination source and computation time restrictions.

A better approach is to assume that the system response is constant within each finite window in the image frame. By partitioning the image frame into only a few windows, the compensation can be greatly simplified. If sensor nonlinearities are dominant, rectangular windows will produce the best results; if lens distortions are dominant, concentric circular windows are more appropriate. Window dimensions must be chosen so that there are no significant artifacts introduced at window boundaries.

If spatial variation in the illumination source or the image sensor response is the significant source of intensity error, a simpler compensation technique may be used. A reference image (REF) of the lightbox intensity field is acquired through an x-ray film of neutral optical density which is nearly the same as that of the radiograph of interest. The ideal system response is assumed to be the entire image frame filled with a constant intensity level equal to the mean. The spatial illumination trend may be modeled by the deviation of data in this image from the mean intensity of the image. Compensation of a subsequently acquired image (A) of the x-ray of interest may be performed by modifying the data at each pixel location in one of two ways. Illumination source trends may be treated as spatial level shifts and are compensated using offset compensation:

$$A(i,j) = A(i,j) + [\text{mean REF} - REF(i,j)] \qquad (1)$$

Sensor response trends may be treated as spatial gain variations and are compensated using:

$$A(i,j) = A(i,j) \times [\text{mean REF} / REF(i,j)] \qquad (2)$$

Gain and offset compensation are easily implemented. The lens aperture must be the same when acquiring images REF and A. If there is a significant difference in the average levels of images REF and A, offset compensation will introduce artifacts into the image data.

DYNAMIC RANGE EXPANSION

The dynamic range of the acquisition system (i.e. the maximum x-ray optical density that can be imaged) is limited by the maximum lightbox intensity and the camera response. Typical system dynamic ranges are

between 1.5 and 2.5. In general this is not adequate for NDE x-ray imaging. The effective dynamic range of a given acquisition system may be increased beyond its actual dynamic range.

The camera and acquisition hardware provide a mapping from a finite intensity range to a finite numerical range (see figure 1). The camera gamma and AGC controls determine the slope and linearity of this mapping. The entire mapping is shifted left or right by changing the lens aperture and/or the lightbox intensity. It is assumed that the shape of the curve is not changed by such a translation. Saturation occurs at both ends of this mapping because of sensitivity limitations in the camera image sensor.

The x-ray optical density range imaged is determined by the horizontal position of this mapping. A different range may be acquired by translating the mapping as described above.

The x-ray of interest is digitized more than once, with each acquisition covering a different subrange of the entire optical density range in the radiograph (see figure 2). The subranges chosen should overlap slightly so that saturation effects may be minimized.

The individual acquisitions (subimages) are then numerically combined into a single image. If the combined image is to be processed by the same hardware used for image acquisition, then it is desirable to limit the numerical intensity range of the combined image to that of its subimages. This requires intensity compression of the subimages prior to combination. Such compression can be accomplished easily using an intensity look-up-table (LUT) transformation. The subimages are combined using a two-step process. First, regions of each subimage that were saturated during acquisition and regions of each subimage that overlap with regions of another subimage are eliminated. Each subimage is then numerically shifted according to its corresponding optical density subrange. The subimages are simply added together to form the combined image (see figure 3).

Proper selection of compression and shift amounts for each subimage requires system calibration. This is best accomplished by applying the dynamic range expansion algorithm to a calibrated grey-scale step wedge pattern so that intensity levels of the combined image can be compared to known values.

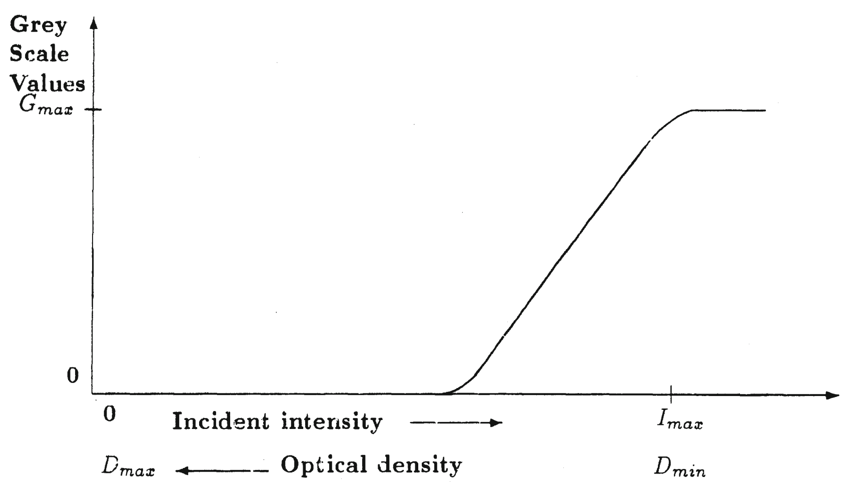

Fig. 1. Idealized system response.

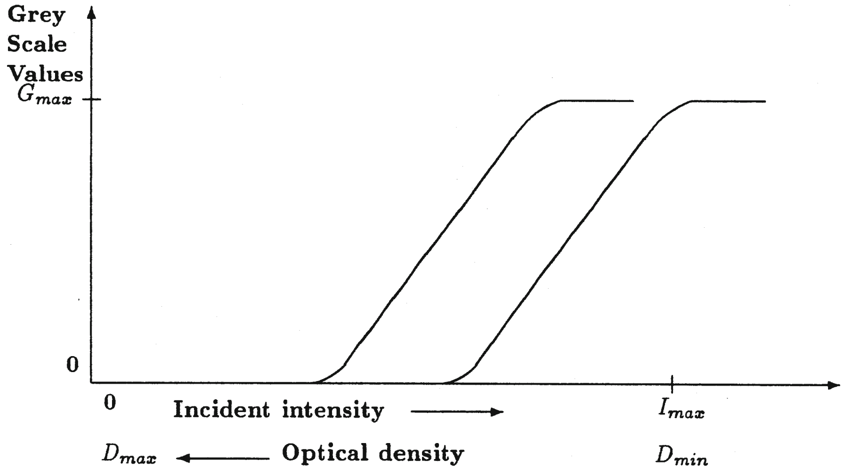

Fig. 2. Acquisition of two different optical density subranges.

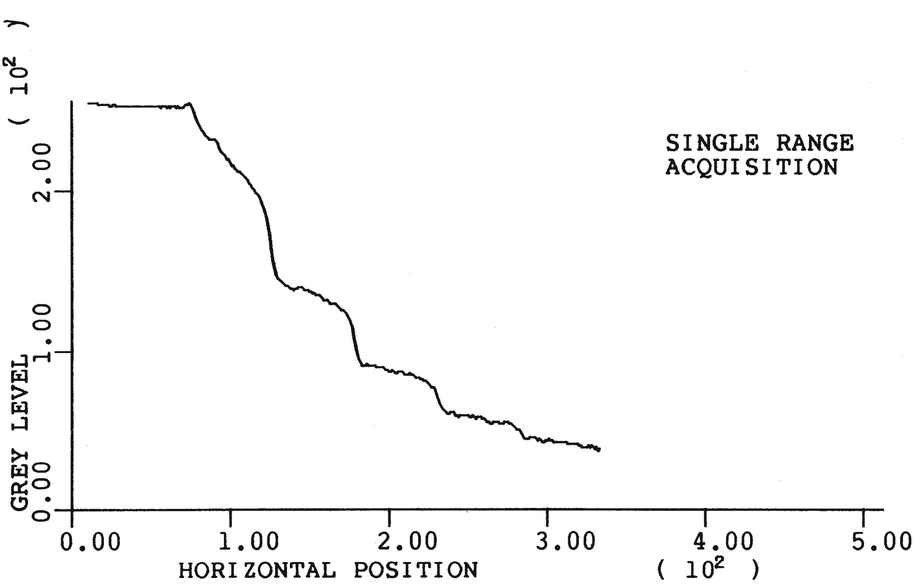

Fig. 3. Combination of two subimages to produce composite image.

EXPERIMENTAL RESULTS

An algorithm to implement both offset and gain compensation was implemented. The reference image used was an image of the lightbox alone. The test image was a neutral radiograph of optical density approximately 1.0. The variances of the test image data before and after compensation are given in Table 1. The reduction in variance is due to removal of a significant illumination trend. The residual variance is primarily due to system noise and nonuniformities in the neutral radiograph such as dropouts and dust particles.

Table 1. Variance reduction produced by trend compensation algorithm.

METHOD	ORIGINAL	COMPENSATED
Gain compensation	45.3818	0.3682
Offset compensation	45.1597	0.2447

Table 2. Expansion algorithm performance vs. system performance.

METHOD	OPTICAL DENSITY RANGE COVERED
Normal acquisition	2.3
Expansion algorithm	4.2

An algorithm was implemented to perform dynamic range expansion using two subimages. Calibration of the algorithm was not performed. An uncalibrated step wedge pattern was digitized both normally and using the expansion algorithm. The measured optical density ranges covered by each image are indicated in Table 2.

A one-dimensional pixel intensity slice through the center of the pattern was plotted for each image (see figures 4 and 5). The number of steps in the pattern that can be resolved has been doubled by using the expansion algorithm. The non-linearity in the step levels in each image is due to intensity errors in the acquisition system. Some of the nonlinearity in the image acquired using the expansion algorithm is due to the false assumption that the incident intensity to grey level mapping shape is unaffected by translation. These nonlinearities can be compensated by system and algorithm calibration.

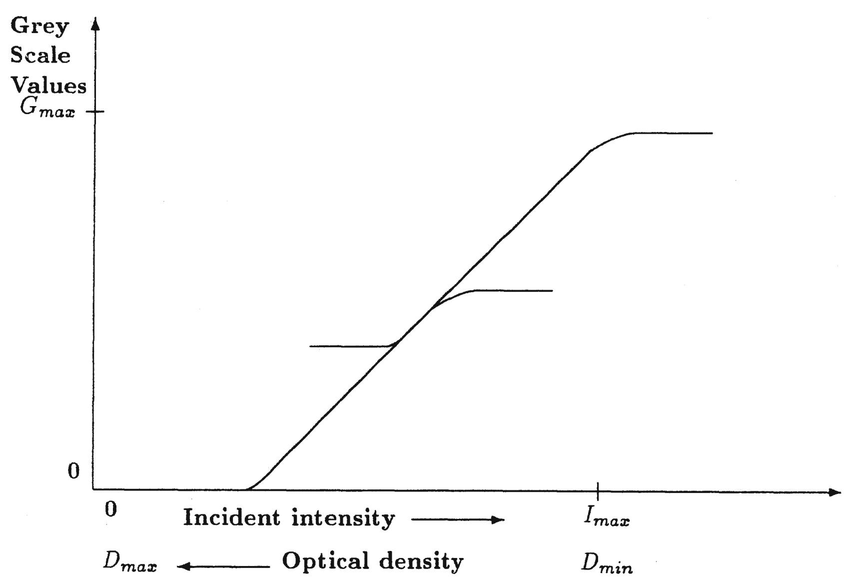

Fig. 4. 1-D pixel intensity slice for normally acquired step wedge image.

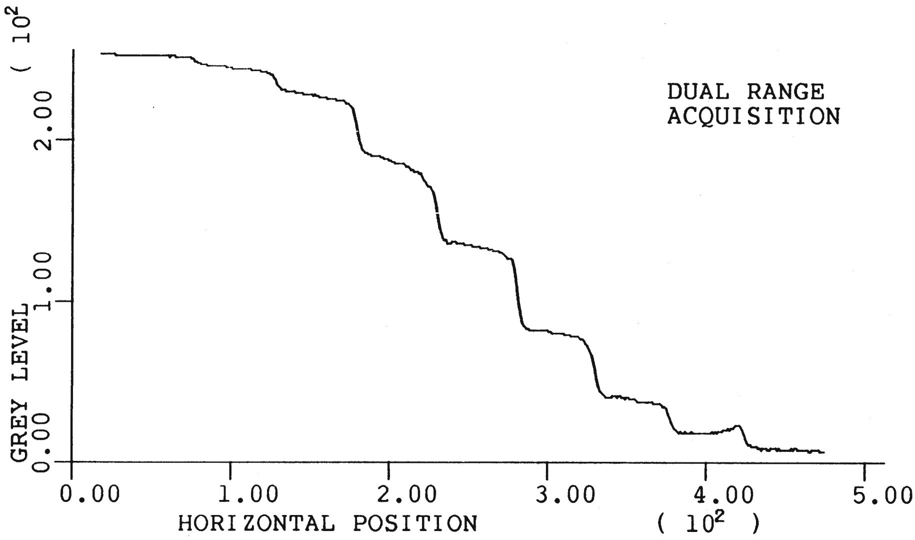

Fig. 5. 1-D pixel intensity slice for step wedge image acquired using expansion algorithm.

APPLICATIONS

Intensity correction and dynamic range expansion may be applied to any image acquisition system. These techniques are particularly well suited to NDE x-ray image processing because of the inherent need to characterize fine image detail. Intensity correction is necessary whenever accurate quantitative image data is required. Dynamic range expansion is most useful when digitizing radiographs of parts where the high optical density regions of the image corresponding to the part are surrounded by low optical density areas due to the background. Examples of such parts are pipe welds and turbine blades.

CONCLUSION

Error compensation for an image acquisition system should minimize intensity and geometric distortions and attempt to circumvent system limitations. Intensity errors may be compensated by modeling system response using a calibrated grey-scale pattern. Illumination trends may be compensated by modeling system response using a neutral-density radiograph. System dynamic range limitations may be exceeded when acquiring an image by capturing and combining several subimages.

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